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Rapid water quality change in the Elwha River estuary complex during dam removal

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Abstract

Dam removal in the United States is increasing as a result of structural concerns, sedimentation of reservoirs, and declining riverine ecosystem conditions. The removal of the 32 m Elwha and 64 m Glines Canyon dams from the Elwha River in Washington, U.S.A., was the largest dam removal project in North American history. During the 3 yr of dam removal—from September 2011 to August 2014—more than ten million cubic meters of sediment was eroded from the former reservoirs, transported downstream, and deposited throughout the lower river, river delta, and nearshore waters of the Strait of Juan de Fuca. Water quality data collected in the estuary complex at the mouth of the Elwha River document how conditions in the estuary changed as a result of sediment deposition over the 3 yr the dams were removed. Rapid and large-scale changes in estuary conditions—including salinity, depth, and turbidity—occurred 1 yr into the dam removal process. Tidal propagation into the estuary ceased following a large sediment deposition event that began in October 2013, resulting in decreased salinity, and increased depth and turbidity in the estuary complex. These changes have persisted in the system through dam removal, significantly altering the structure and functioning of the Elwha River estuary ecosystem.

Impacts from human activities have fundamentally changed ecosystems around the world (Vitousek et al. 1997). Land-use change, in particular, has altered the amount of sediment entering watersheds and being delivered to the ocean (Syvitski et al. 2005). Activities such as logging and urban development have increased the amount of sediment entering rivers and the ocean (Walling and Fang 2003), while the construction of dams has significantly decreased the amount of sediment reaching the ocean (Vörösmarty et al. 2003). These changes can affect sediment budgets at multiple scales, from a single river system to the world's ocean. Altered sediment delivery can also have long-term effects on abiotic and biotic characteristics of ecosystems (Henley et al. 2000; Airoldi 2003; Thrush et al. 2004).

Additional Supporting Information may be found in the online version of this article.

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The number of dams worldwide is continually increasing in an effort to address rising demands for power and water (World Commission on Dams 2000). In the United States, however, there has been an increase in the number of dam decommissioning projects (Pohl 2002; O'connor et al. 2015) in response to concerns about structural integrity, sedimentation of reservoirs, and declining ecological conditions (Born et al. 1998; Aspen Institute 2002). In many recent removals, the cost of maintaining or retrofitting dams, coupled with the social and ecological risks, outweighed the benefits the dams generated, making removal a viable option (Aspen Institute 2002).

Dams can affect the physical properties of downstream river reaches by altering flow (e.g., attenuating or decreased peak flows), changing water temperature, and increasing the coarseness of the stream bed by impeding the transport of sediment downstream (Stanley and Doyle 2003). Dams also create a physical barrier for migrating species, including many declining anadromous fish populations (Heinz Center 2002). Although dam removal can immediately alleviate some of these changes, removal is not without consequence. Depending on the lifespan of a dam and the properties of the

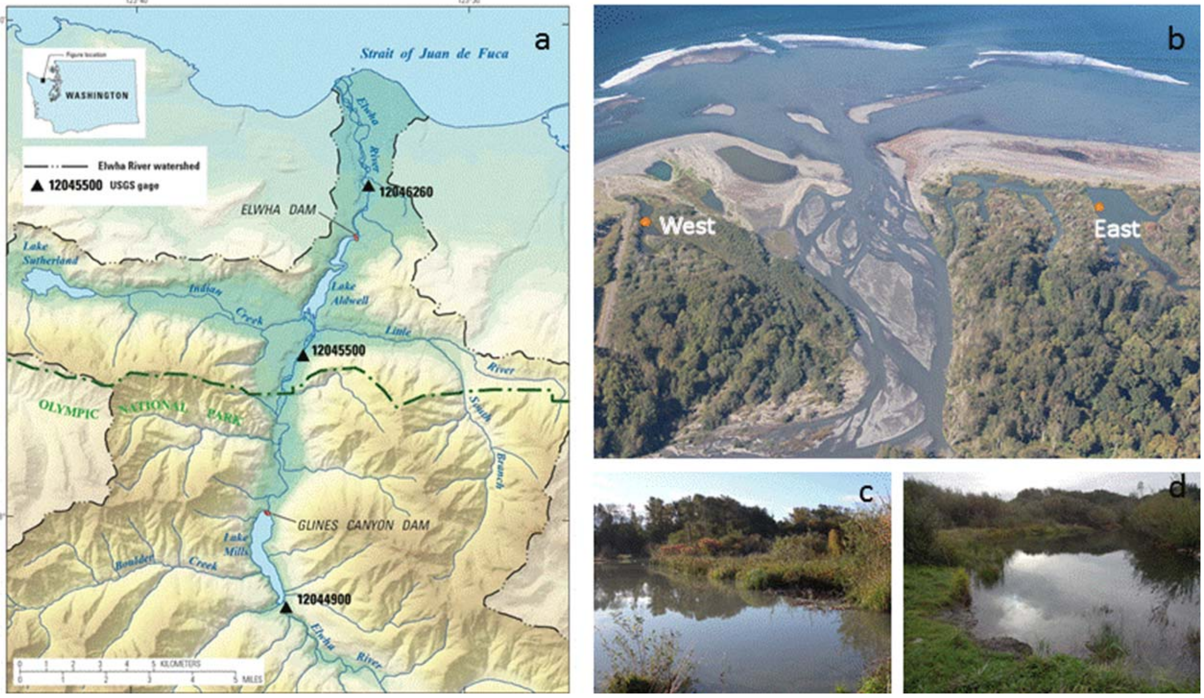

Fig. 1. (a) Elwha River and dam locations; (b) estuary complex at the mouth of the Elwha River (September 2013); (c) east estuary; (d) west estuary. Orange dots denote the location of the YSI sondes. (Photos by A. Ritchie and M. Foley)

surrounding watershed, vast amounts of sediment can accumulate in the dam reservoir. Estimated amounts of reservoir sediment stored behind recently removed dams range from 1000 m^3 to over 21,000,000 m^3 (Grant and Lewis 2015). The amount and rate of reservoir sediment released during and following dam removal depends on a number of factors, including dam removal method (e.g., instantaneous or staged removal), grain size, cohesion, and consolidation of the sediment deposits, and the timing and magnitude of high flow events (Sawaske and Freyberg 2012). The magnitude and duration of sediment transport following dam removal can fundamentally change downstream physical conditions and drive changes in ecosystem structure and functioning (Poff and Hart 2002). However, much of our knowledge on the effects of dam removal comes from relatively short-duration studies of small, low-head dams (Doyle et al. 2005; Lorang and Aggett 2005; Sawaske and Freyberg 2012).

The removal of the Elwha and Glines Canyon dams on the Elwha River in northwestern Washington (Fig. 1) was the largest dam removal in North American history based on size and the total amount of sediment released. The staged removal of both dams took 3 yr to complete. Dam removal commenced in September 2011; the Elwha Dam was fully removed in March 2012, allowing for the associated reservoir, Lake Aldwell, to drain completely at that time. Lake Mills, upstream of the Glines Canyon Dam, was fully drained in late October 2012 and the dam was completely removed in September 2014. Sediment in the reservoirs was free to be transported downstream at the time of reservoir draining, although considerable transport occurred once delta sediments reached the partially removed dams.

An estimated $21 \pm 3 \times 10^6$ m^3 of fine and coarse-grained sediment accumulated behind the Glines and Elwha dams prior to dam removal (Randle et al. in press). Modeling conducted prior to dam removal predicted that approximately 50–60% of accumulated sediment would erode from the reservoirs, with the river transporting most of the material to the Strait of Juan de Fuca (Randle et al. 1996; Konrad 2009). What came to pass, however, was considerable deposition at the river delta during the first 2 yr of dam removal. Gelfenbaum et al. (In press) measured approximately 2.5×10^6 m^3 of deposition, effectively moving the delta approximately 200 m offshore (Fig. 2). During this same time period, water column turbidity in the river increased by three orders of magnitude compared to natural levels in the Elwha River upstream of the dams (Curran et al. 2013; Magirl et al. in press).

Changes in sediment deposition and water column turbidity could substantially alter river, coastal, and nearshore habitats downstream of the dams, which were thoroughly altered due to the presence of the dams (D.O.I. 1995; Duda et al. 2008, 2011b). Of particular interest in the Elwha River system is the estuary complex at the mouth of the river (Fig. 1). These well-defined pocket estuaries support a diverse population of macroinvertebrates (Duda et al. 2011a) and plant communities (Shafroth et al. 2011). Like other estuaries in the Puget Sound, they are also important nursery habitat for

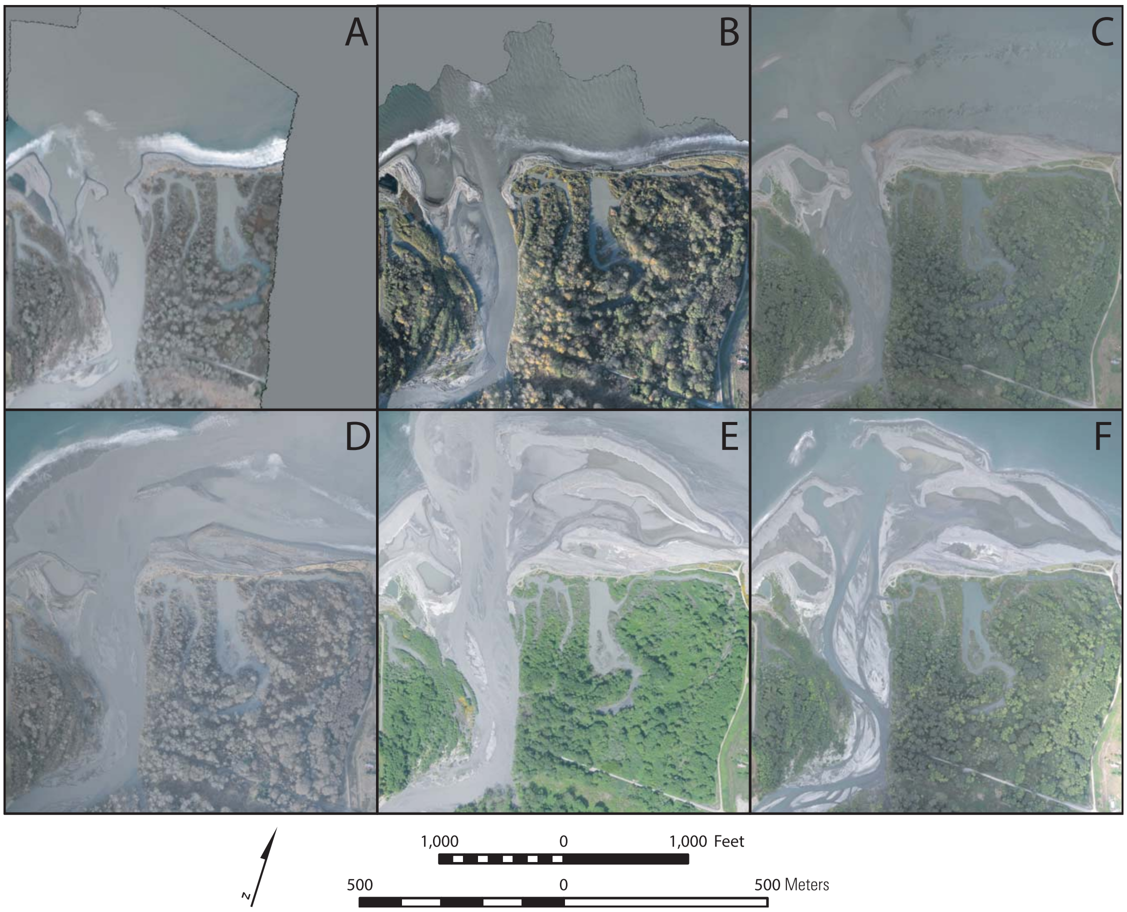

Fig. 2. Photos showing the evolution of the Elwha River mouth and estuary complex during dam removal. (A) 19 March 2012 (tide height 1.5 m; river discharge 1930 $ft^3\ s^{-1}$) (dam removal had started but Elwha Dam was not yet completely removed); (B) 08 November 2012 (tide height 1.3 m; river discharge 1260 $ft^3\ s^{-1}$); (C) 26 August 2013 (tide height 1.6 m; river discharge 431 $ft^3\ s^{-1}$); (D) 15 January 2014 (tide height 1.4 m; river discharge 1360 $ft^3\ s^{-1}$); (E) 14 May 2014 (tide height 1.3 m; river discharge 2420 $ft^3\ s^{-1}$); (F) 12 August 2014 (tide height 1.5 m; river discharge 569 $ft^3\ s^{-1}$). (Photos by A. Ritchie)

many fish species, including several salmonids (Simenstad et al. 1982; Shaffer et al. 2008; Duda et al. 2011a). Prior to dam removal several factors controlled water quality in the estuary complex—including tidal flushing, river discharge, and ocean conditions—resulting in daily fluctuations in depth, salinity, and temperature (Magirl et al. 2011).

The likelihood for change in the estuary complex following dam removal was high, including negative impacts to water and habitat quality, but no specific predictions for the type and rate of change in the estuary were made. We present data that show the timing and magnitude of water quality changes in the estuary complex during dam removal from October 2011 through September 2014 and compare these conditions to data from 2008 and 2009, prior to dam removal. This study is an important contribution to the dam removal literature because it is the only published study to examine how dam removal affects abiotic conditions in coastal habitats; the length of the water quality data record is extensive compared to other dam removal studies; and the scale of dam removal and sediment movement is larger than any other dam removal to date. As dam removal is increasingly added to the management toolbox, it is important to understand the short- and long-term outcomes of this river restoration technique in a variety of habitats.

Methods

Study area

The Elwha River drains a glaciated, mountainous watershed that terminates at the Strait of Juan de Fuca approximately 9 km west of the city of Port Angeles, Washington, U.S.A. The Elwha watershed is 833 km^2 in area, with 83% of the watershed contained within the boundaries of Olympic National Park. A steep precipitation gradient exists, with annual precipitation averages of 6000 mm and 1000 mm at the headwaters and river mouth, respectively (Duda et al. 2011b). There are two annual peaks in river flow driven by rainfall in the winter months and snowmelt in the late spring and early summer. Average annual discharge of the Elwha River, measured at the USGS McDonald Bridge gauging station (#12045500; http://waterdata.usgs.gov/wa/nwis/uv?site_no=12045500) is 43 $m^3 s^{-1}$.

The Elwha River estuary occurs at the confluence of the Elwha River and the Strait of Juan de Fuca, the water body that connects Puget Sound to the Pacific Ocean. The estuary complex is approximately 0.35 km^2 in size, and is comprised of two pocket estuaries—small estuaries behind a barrier beach that are tidally influenced (Beamer et al. 2003)—to the east (0.25 km^2) and west (0.1 km^2) of the river (Fig. 1b). The estuaries were former distributary channels that were modified in the 20^{th} century by channelization, damming, and diking, which limited the river to a single channel. A large portion of the estuary area is located on the Lower Elwha Klallam tribal reservation.

Over the past century, the Elwha River was altered by the presence of two hydroelectric dams. The 32 m Elwha Dam was constructed at river kilometer (distance from the mouth of the river, hereafter rkm) 7.9 from 1910 to 1913 impounding Lake Aldwell, a reservoir that stored 10×10^6 m^3 of water. The Glines Canyon Dam was completed in 1927 at rkm 21.6. This concrete arch dam was 64 m in height and its reservoir Lake Mills stored 50×10^6 m^3 of water. The dams were constructed without provisions for fish passage, which caused precipitous declines in once abundant anadromous salmonids (Wunderlich et al. 1994; Brenkman et al. 2008; Pess et al. 2008), as well as other changes to the physical and biological structure and function of the ecosystem (e.g., Wunderlich et al. 1994; Duda et al. 2008; Morley et al. 2008). Recognizing an opportunity to recover imperiled salmon populations, as well as resolving legal issues surrounding Federal Regulatory Energy Commission relicensing (*see* Gowan et al. 2006; Winter and Crain 2008 for reviews), the United States Congress passed The Elwha River Anadromous Fisheries and Ecosystem Restoration Act (Public Law 102-495) in 1992, which ultimately paved the way for dam removal to occur (D.O.I. 1995).

Study design

We deployed sondes measuring salinity (ppt) and temperature (°C) (YSI Incorporated, *600-LS* sonde) in the east estuary from June to October 2008 and May to August 2009, and in the west estuary from May to October 2009 (Fig. 1b) to characterize water quality in the estuaries prior to dam removal. We deployed sondes measuring salinity (ppt), temperature (°C), depth (m), and turbidity (NTU) (YSI Incorporated, *OMS 660* sonde) at the same locations in the east and west estuaries in June and August 2011, respectively, to characterize estuary water quality during dam removal. All parameters were measured and logged every 15 min, and we serviced the instruments and downloaded the data at approximately 30-d intervals. Gaps in the data occurred when instruments were being serviced or calibrated, or when they were compromised (e.g., sediment accumulated in protective sleeve or buried the sensors) during high sedimentation events.

We summarize the time series data using a range of metrics over different temporal scales to capture the rapidly changing physical conditions in the estuary and to document changes during specific time periods during dam removal. We calculated monthly summary statistics (minimum, maximum, mean, median, standard degrees of freedom, and variance) for all water quality variables by water year (01 October through 30 September; http://water.usgs.gov/nwc/explain_data.html) for 2008, 2009, 2012, 2013, and 2014 (hereafter water years will be referred to as, e.g., WY14) to assess the timing and magnitude of change. Following Magirl et al. (in press), we also binned the data into nine distinct time intervals that correspond to major events during the dam removal process (e.g., release of sediment from Lake Aldwell) or hydrologic periods (e.g., summer flows). We used analysis of variance (ANOVA) measures to test for differences in salinity, depth, temperature, and turbidity values across the following nine distinct time intervals: (1) before dam removal (WY08 and WY09); (2) early dam removal (01 October 2011–22 March 2012); (3) Lake Aldwell release (23 March 2012–14 May 2012); (4) Summer 1 (15 May 2012–13 October 2012); (5) Lake Mills release (14 October 2012–10 July 2013); (6) Summer 2 (11 July 2013–27 September 2013); (7) Winter 3 (28 September 2013–31 March 2014); (8) Freshet 3 (01 April 2014–31 May 2014); and (9) Summer 3 (01 June 2014–30 September 2014). We used a pair-wise Tukey test to test for differences between the nine dam removal time intervals. Prior to using ANOVA measures we used a fourth root transformation on the data to improve the homogeneity of variances. Data were analyzed with R (version 3.0.0).

We also created indices from the salinity and turbidity data that were useful for predicting the timing of potential biological changes in the estuary. We calculated the proportion of time estuary conditions were characterized by four salinity habitat classes—fresh (0–0.5 ppt), oligohaline (0.5–5 ppt), mesohaline (5–18 ppt), and polyhaline (18–30 ppt) for each dam removal time interval. These salinity habitat classes reflect salinity thresholds that drive changes in the benthic fauna of estuaries (Dauer 1993). We also calculated the proportion of time estuary conditions were characterized by five turbidity classes: < 50 NTU, < 250 NTU, < 500 NTU, < 1000 NTU, and > 1000 NTU. The cutoffs for the first two categories were drawn where biological processes in the estuary, such as productivity (Lloyd et al. 1987) and feeding (Reid et al. 1999), respectively, could be affected by elevated levels of suspended sediment.

Results

We saw a dramatic shift in salinity, temperature, depth, and turbidity dynamics in the estuary complex during the dam removal process. Prior to dam removal (WY08 and

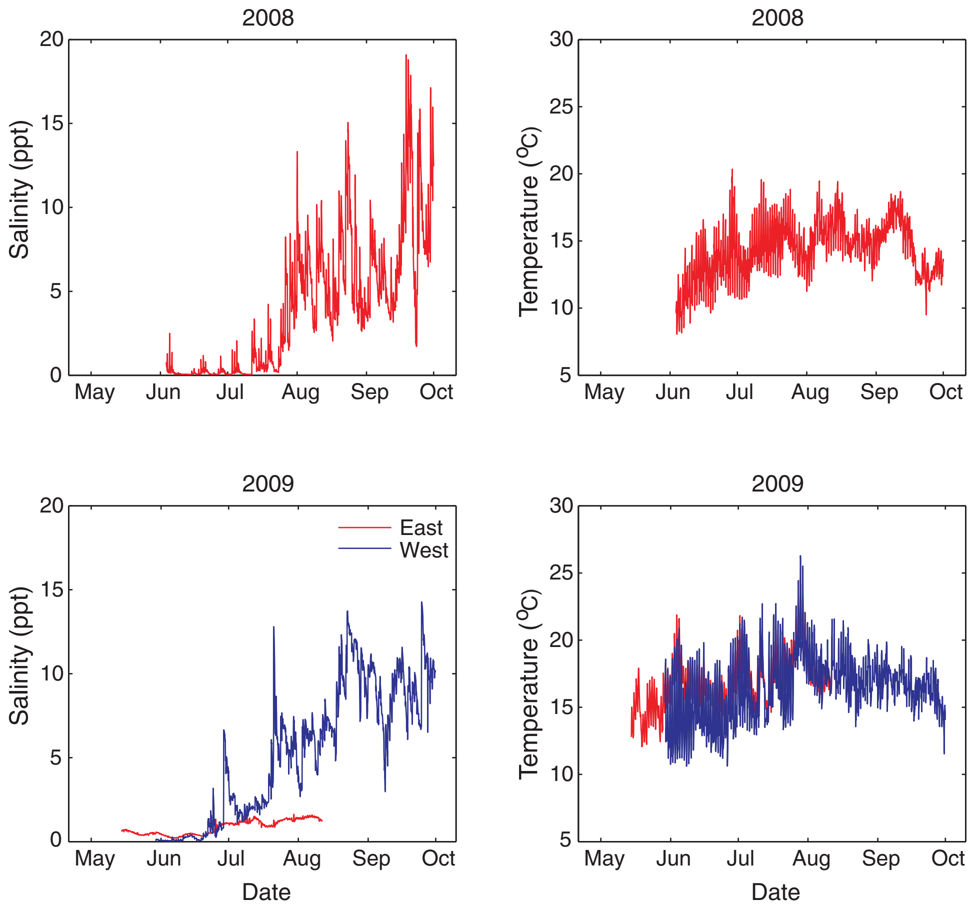

Fig. 3. Time series data for the east and west estuaries for salinity (ppt) and temperature (°C) from 2008 and 2009, prior to dam removal.

WY09), estuarine salinity and temperature values fluctuated over a large range multiple times a day (Fig. 3). These fluctuations continued through Summer 1 of dam removal, with salinity values ranging between 0.01 ppt and 31.6 ppt and temperatures from near freezing in winter months to over 20°C in summer months (Figs. 4a, 5, Supporting Information Table 1). Depth was similarly variable during the first three periods of dam removal, fluctuating between 0.2 m to 1.2 m (Fig. 4a). Turbidity was low during early dam removal but increased when Lake Aldwell drained. During this time period, major increases in turbidity covaried with river discharge (Fig. 4a). Turbidity levels decreased during Summer 1 but were significantly higher in both estuaries during Summer 1 (mean $\pm$ sd; 40.6 $\pm$ 42.6 NTU) than they were during Early Removal (17.3 $\pm$ 14.1 NTU) (Fig. 6; Table 1).

Absolute values and variability of all water quality metrics changed rapidly in the estuary after Lake Mills started spilling sediment in October 2012 (Figs. 4–6). Beginning in February 2013 in the east estuary and in May 2013 in the west estuary, overall salinity decreased and the variability in salinity values at daily, weekly, and monthly scales was minimal (Figs. 4b, 5, Supporting Information Table 1). Salinity values remained low for the remainder of our measurements. There was a significant difference in salinity values across many time intervals (east—$F_{8,86980} = 9326$, $p < 0.001$; west—$F_{8,83703} = 13{,}457$, $p < 0.001$), driven by season in the early stages of dam removal (Early Removal through Summer 1) and continual freshening in the later stages of dam removal (Fig. 6). Pair-wise comparisons showed that salinity values during similar seasons were also significantly different (summer 1 = 0.7 $\pm$ 1.2 ppt; summer 2 = 0.1 $\pm$ 0.01 ppt; summer 3 = 0.05 $\pm$ 0.01 ppt; Table 1; $p < 0.001$ for all significant pair-wise comparisons). Salinity conditions in the east estuary were similar during the release of sediment from the Aldwell and Mills reservoirs ($p = 0.99$) and during freshet 3 and summer 3 ($p = 0.67$). Salinity conditions in the west estuary were significantly different across all time intervals ($p > 0.05$).

The decrease in salinity following the release of sediment from Lake Mills in October 2012 drastically shifted the presence and persistence of salinity habitats in the estuaries (Fig. 7a). Prior to dam removal, the east estuary predominantly

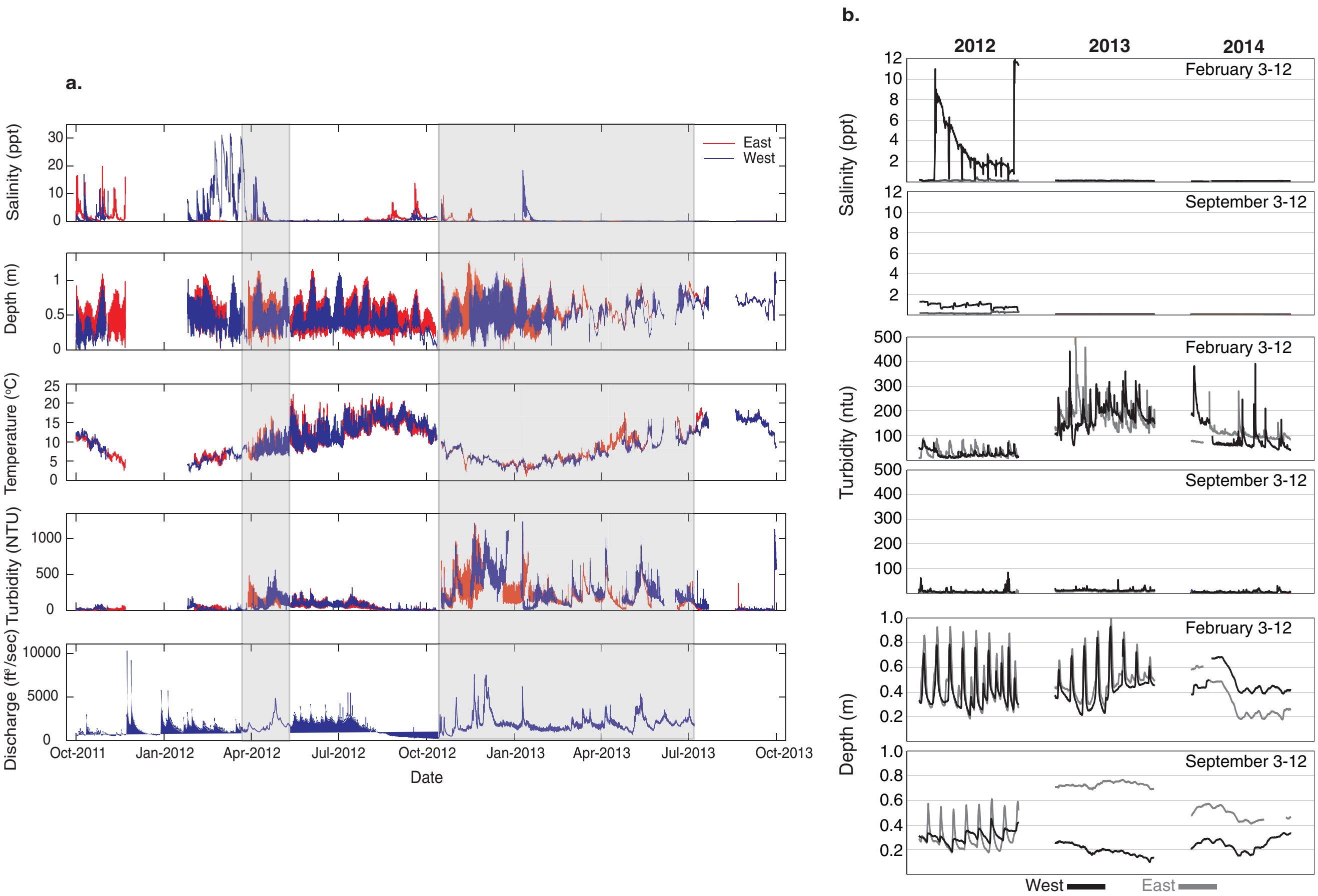

Fig. 4. (a) Time series data for the east and west estuaries for salinity (ppt), depth (m), temperature (°C), and turbidity (NTU) from 01 October 2011, to 30 September 2014. The grey boxes denote when the Aldwell and Mills reservoirs drained and sediment started moving out of the reservoirs. (b) Time series data comparing salinity (ppt), turbidity (NTU), and depth (m) conditions during 03–12 February 2012, 2013, and 2014 and 03–12 September 2012, 2013, and 2014 for the west (black) and east (grey) estuaries.

fluctuated between fresh (34%), oligohaline (36%), and mesohaline (29%) conditions with occasional polyhaline (1%) events. During early removal, the east estuary was slightly fresher (48% fresh, 45% oligohaline), with fewer mesohaline events (7%). The Lake Aldwell release coincided with the end of winter flows and the beginning of the spring freshet, so salinity conditions during this time were predominantly fresh (96%). Oligohaline conditions returned during Summer 1 (39%) and during the beginning of the Lake Mills release (9%) after which the salinity habitat in the estuaries was fresh 100% of the time.

Water depth in the estuaries began to increase in the east estuary in February 2013 and in the west estuary in April 2013 (Fig. 4, Supporting Information Table 2). Similar to salinity, daily fluctuations in water depth also largely disappeared from the system at that time (Fig. 4b). The minimum depth in the east estuary increased from 0.02 m to 0.6 m in the summer of 2013, decreasing the difference between minimum and maximum depth values in the estuaries (Figs. 4a, 5, Supporting Information Table 2). Estuary depth fluctuated more during WY14 in response to river discharge and migration of the main river channel (Figs. 2, 4a). Similar to salinity, depth was significantly different across many dam removal intervals in the east estuary ($F_{7,81978} = 3498$, $p < 0.001$) and significantly different across all time periods in the west estuary ($F_{7,80689} = 2489$, $p < 0.001$) (Fig. 6; Table 1). Water depth in the east estuary was similar during early dam removal, Summer 1 and Summer 3 ($p = 0.99$ for all pairwise combinations of those three periods).

The variability in water temperature decreased beginning in December 2012 (Fig. 5, Supporting Information Table 3) and fluctuated diurnally with air temperature rather than semidiurnally with the tide (Fig. 4b). Estuary temperature was significantly different across all dam removal phases in the west estuary ($F_{8,\ 83701} = 18491$, $p < 0.001$), whereas temperature in the east estuary was similar between before dam removal and summer 2 phases ($p = 0.84$), and early removal and the Lake Mills release phases ($p = 0.16$) (Fig. 6; Table 1).

Turbidity levels increased substantially in November 2012 following the release of sediment from Lake Mills (east—

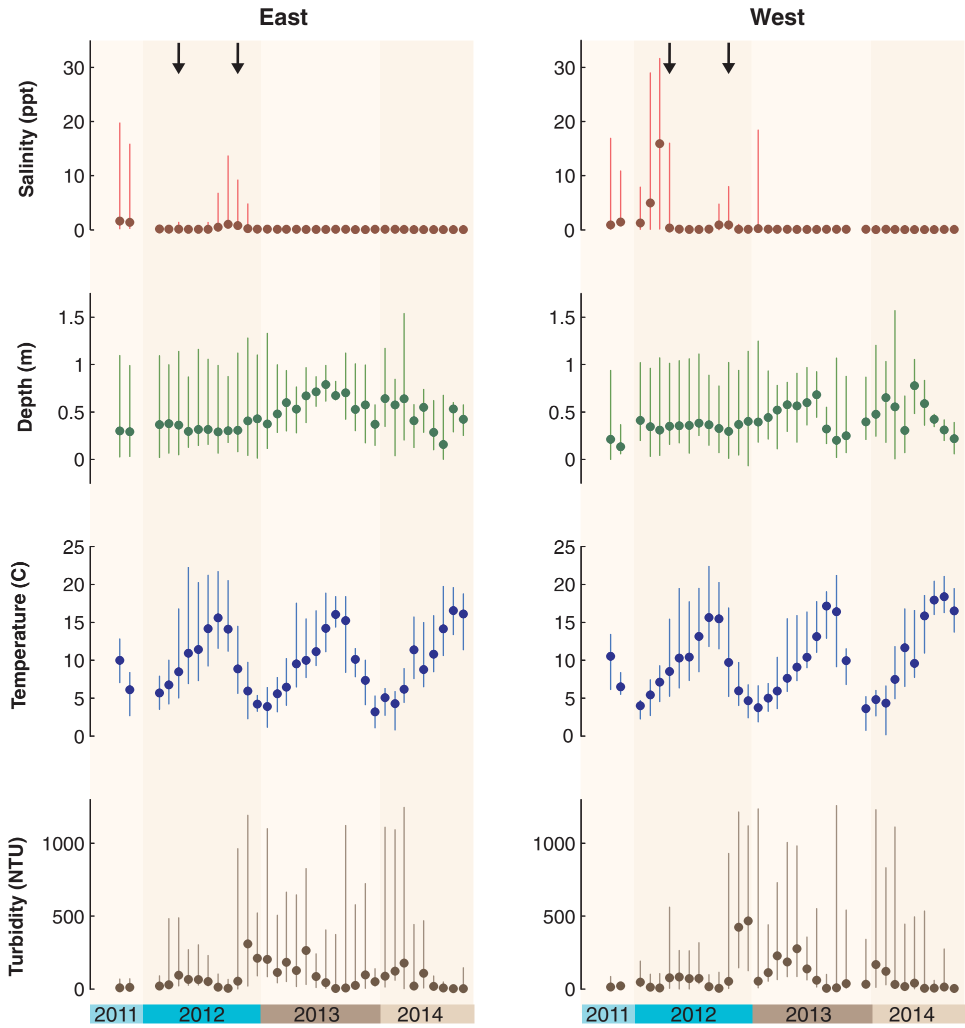

Fig. 5. Monthly median, minimum, and maximum values for salinity (ppt), depth (m), temperature (°C), and turbidity (NTU) from October 2011 through September 2014 for the east estuary only. Arrows denote where sediment from Lake Aldwell and Lake Mills, respectively, started moving downstream.

208 ± 161 NTU; west—265 ± 203 NTU; Figs. 4-6, Supporting Information Table 4). Through the rest of the dam removal process, turbidity values were seasonal; turbidity decreased in Summer 2 (east—9.7 ± 10.2 NTU; west—18.0 ± 17.0 NTU), increased during Winter 3 (east—177 ± 50 NTU, west—162 ± 215 NTU) and Freshet 3 (east—69 ± 65 NTU, west—60 ± 85 NTU) and decreased again during Summer 3 (east—12.0 ± 17.4 NTU, west—13.0 ± 30.0 NTU).

Turbidity events in WY13 and WY14 were not only higher than WY12, but the events were also longer in duration, particularly after March 2013 (Fig. 4, Supporting Information Table 4). Overall turbidity was highest in the east estuary when Lake Mills was draining. During this period, the estuary was too turbid to support primary production 90% of the time and impaired foraging of fish and invertebrates of 25% of the time (Fig. 7b). Turbidity levels during the main summer growing season varied across the three water years. Turbidity conditions exceeded the primary productivity threshold 30% of the time in WY12, 2% in WY13, and 5% in WY14 (Fig. 7b).

Discussion

Fundamental changes to the estuary

The estuary complex at the mouth of the Elwha River has historically been an important habitat for many salmon species (Duda et al. 2011a; Quinn et al. 2013) and is an important component of the restoration occurring on the Elwha River following the removal of the Elwha and Glines Canyon dams. The magnitude and rate of change in the Elwha estuary complex during the 3 yr of dam removal have been large and rapid (Fig. 2). The decades-worth of annual sediment load that moved through the Elwha River system during dam removal is on par with flows from extreme events—such as wildfires,

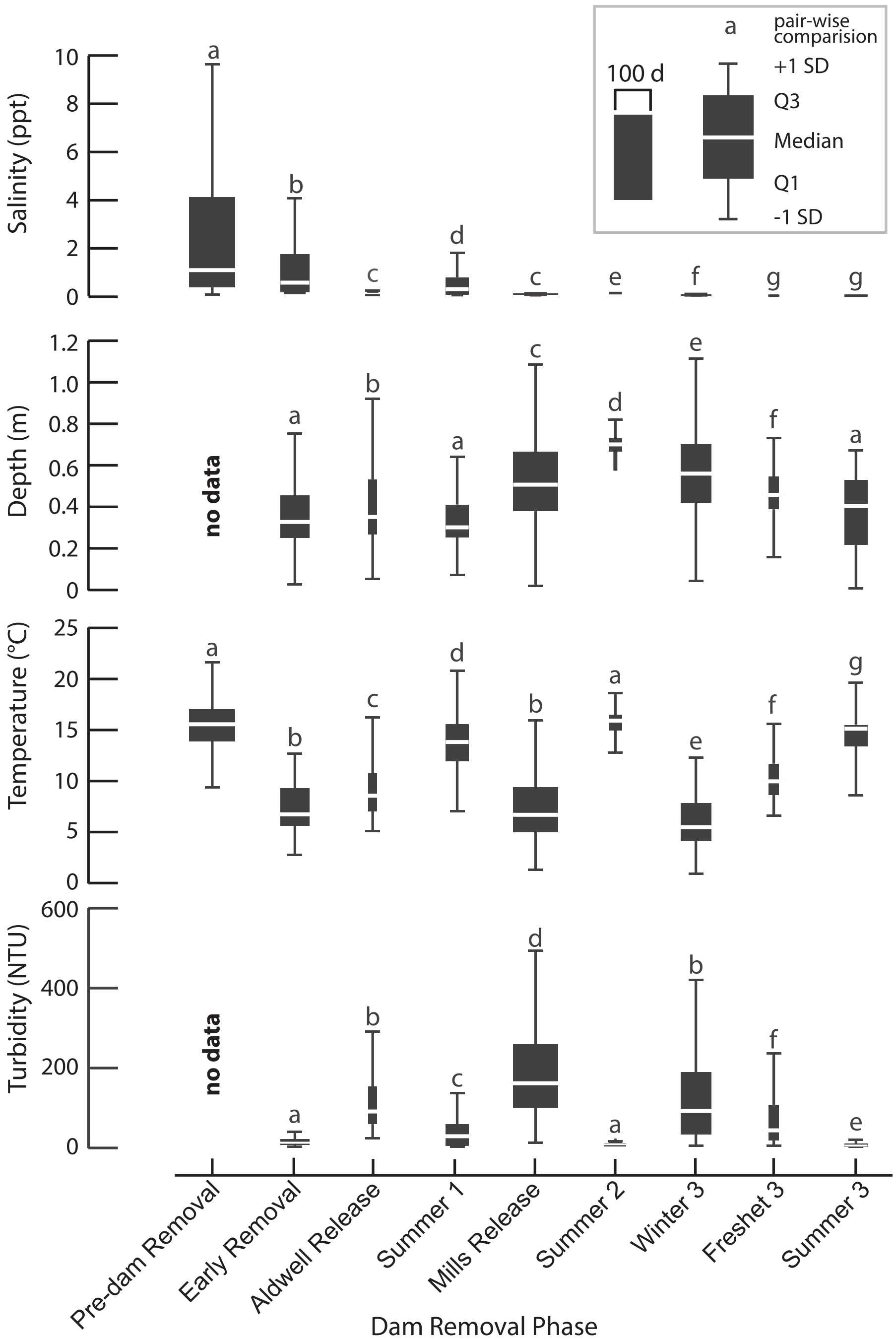

Fig. 6. Box-plots showing differences in (a) salinity (ppt), (b) depth (m), (c) temperature (°C), and (d) turbidity (NTU) values for distinct time intervals before and during dam removal. The width of each box is scaled to the number of days in each time interval. Different letters above the box plots denote significant pair-wise differences between time periods ($p < 0.05$).

typhoons, and volcanoes—that deliver large amounts of land-derived sediment to aquatic systems over short periods of time (Major et al. 2000; Milliman and Kao 2005; Jennerjahn et al. 2013; Magirl et al. in press) (Fig. 8).

Movement and deposition of sediment within the Elwha watershed, mediated by the staged deconstruction of both dams, were likely the major drivers directly and indirectly affecting water quality in the estuary complex. Prior to dam removal, estuary salinity, depth, and temperature fluctuated multiple times a day as semi-diurnal tides pushed seawater into the estuary complex (Magirl et al. 2011). Tidal influence started to diminish in November 2012 when the lower river

Table 1. Single factor ANOVA and Tukey post hoc test results for dam removal period using fourth root transformed data.

Site and parameter	df	Sum of squares	*F*-value	*p*-value	Overall change	Nonsignificant pair-wise interactions ($p > 0.5$)
East salinity	8, 86980	2799, 3263	9326	<0.001	Decrease	• Aldwell release vs. Mills release • Freshet 3 vs. Summer 3
East depth	7, 81978	177.1, 592.8	3498	<0.001	Increase; less variability	• Early removal vs. Summer 1 • Early removal vs. Summer 3 • Summer 1 vs. Summer 3
East temperature	8, 86984	2392, 1520	2392	<0.001	Increase in summer, decrease in winter; less variability	• Early removal vs. Mills release • Pre-dam removal vs. Summer 2
East turbidity	7, 81899	45,781, 39,660	13,506	<0.001	Increase	• Aldwell release vs. Winter 3
West salinity	8, 83703	6877, 5347	13,457	<0.001	Decrease	—
West depth	7, 80689	143.1, 662.9	2489	<0.001	Increase; less variability	—
West temperature	8, 83701	2563, 1450	18,491	<0.001	Increase in summer, decrease in winter; less variability	• Summer 1 vs. Mills release • Summer 2 vs. Winter 3 • Summer 2 vs. Freshet 3 • Summer 2 vs. Summer 3 • Winter 3 vs. Freshet 3 • Winter 3 vs. Summer 3 • Freshet 3 vs. Summer 3
West turbidity	7, 77939	44,615, 40,405	12,294	<0.001	Increase	• Summer 1 vs. Freshet 3

and delta experienced rapid accumulation of sediment, including over a meter of aggradation in the river channel (East et al. 2015) and 100 m of seaward progression of the delta (Gelfenbaum et al. In press). These two substantial changes acted together to reduce the extent of tidal propagation into the estuary complex.

The loss of tidal influence in the estuary complex has directly affected estuarine conditions—and likely the structure and function of the estuary—by changing the estuary from a brackish and tidally influenced system to a perpetually freshwater system (Figs. 4, 5). Historically, tidal influence on estuary conditions was highest in the summer and fall when river discharge was low and conversely lowest in the spring and winter when river discharge was high (Fig. 3; Magirl et al. 2011). However, the new configuration of the river delta has changed this seasonal pattern, with river discharge and channel location emerging as the dominant drivers of water quality in the estuary complex throughout the year. For example, estuary depth was more strongly coupled with river discharge following the loss of tidal influence. High discharge events in WY13 and WY14 resulted in deeper water levels for longer durations than similar discharge conditions produced prior to tidal loss (Fig. 4a). Sediment deposition during high discharge events also altered the configuration of estuary channels that connected the estuaries to the river (Fig. 9). The estuaries were prevented from draining after such events, likely driving the overall increasing depth of the estuaries in WY13 and WY14.

Temperature data also reflect the shift from a tidally- to river-driven system. Prior to WY13, both estuaries exhibited cyclical daily temperature patterns that coincided with tidal fluctuations (Figs. 3, 4) (Magirl et al. 2011). Beginning in WY13, daily temperature fluctuations were limited to a single diurnal cycle (Fig. 4b) and significant temperature decreases in the estuaries were correlated with large river discharge events, particularly during the spring freshet (Fig. 5). Temperature decreases following high discharge events were also more prolonged after the loss of tidal influence. The movement of marine waters—which are generally warmer than estuary waters and air temperature in the winter and cooler in the summer—into and out of the estuary moderated estuary temperatures prior to the Lake Mills interval. Temperature was no longer buffered following the loss of tidal influence and we saw the highest estuary temperatures occurring in Summers 2 and 3 and the lowest temperatures in Winter 3 (Fig. 6). Mean air temperature in Port Angeles, Washington, increased each summer (2012 = 13.2°C, 2013 = 13.7°C, 2014 = 14.1°C) and was coldest in the winter months of WY2014 (2012 = 6.1°C, 2013 = 6.7°C, 2014 = 5.9°C). It is likely that air temperatures had a stronger influence on estuary water temperatures after tidal influence was lost, as is evidenced by the decreased range in water temperature midway through WY2013, particularly during summer months. Minimum water temperature in winter months following the loss of tidal influence tended to be colder. During a stretch of low temperature in December

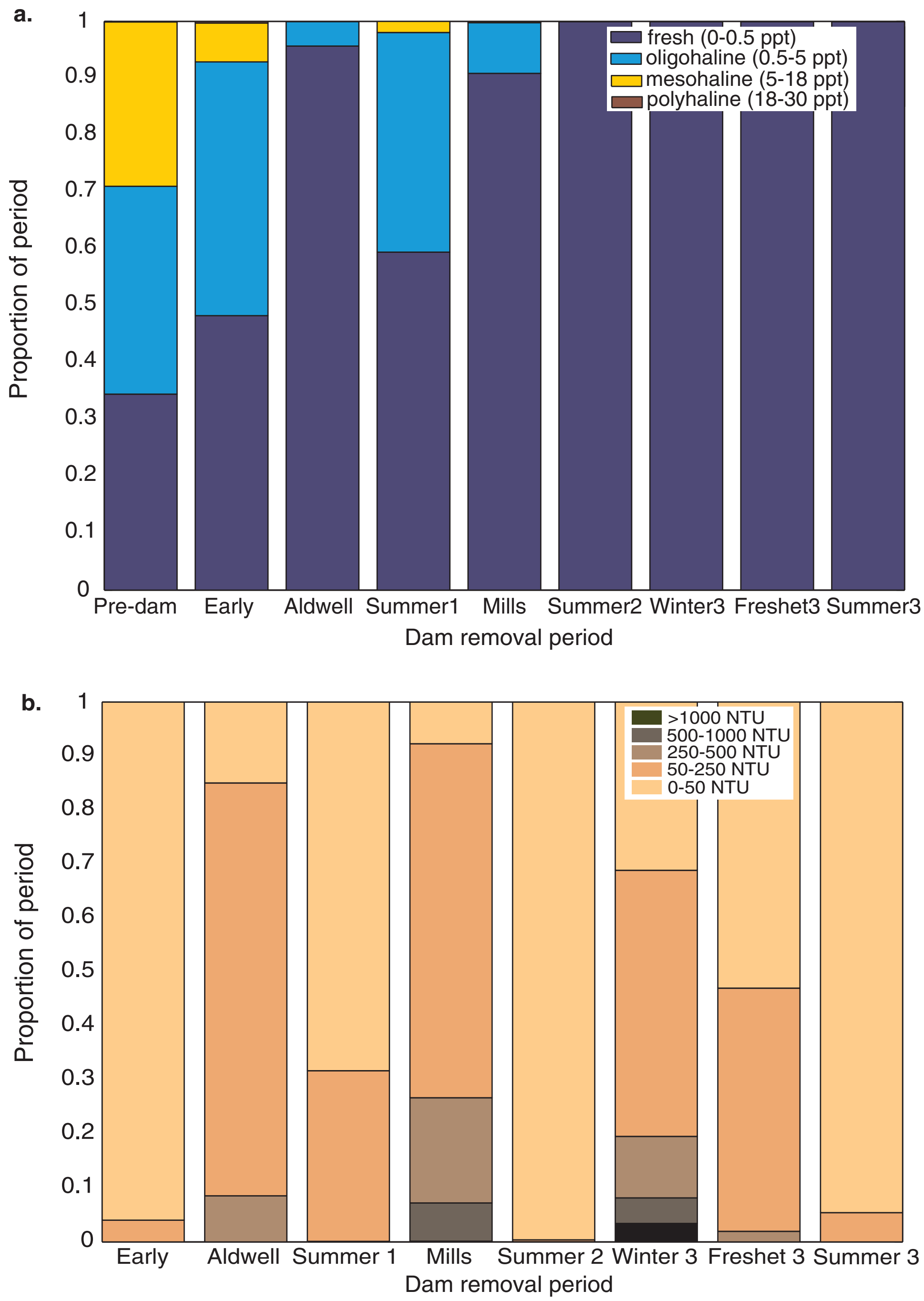

Fig. 7. (a) Proportion of time for each salinity habitat class from May through September for WY2008-2014 (east estuary only); WY2008 and WY2009 are prior to dam removal and WY2012-2014 are during dam removal. (b) Proportion of time in each turbidity class for WY2012-2014 (east estuary only). All turbidity data were collected during dam removal.

2013 the estuaries completely froze over for more than a week, the first such documented event in recent history.

Turbidity levels in the estuaries initially increased in the spring of WY12, which coincided with the draining of Lake Aldwell and the full removal of the Elwha dam. Although turbidity increased in the estuary during this time, the increase was minimal and relatively short-lived. The draining of Lake Mills in October 2012 coincided with a series of moderate storms (Fig. 4a) that moved a significant amount of sediment through the river (Warrick et al. in press). Turbidity

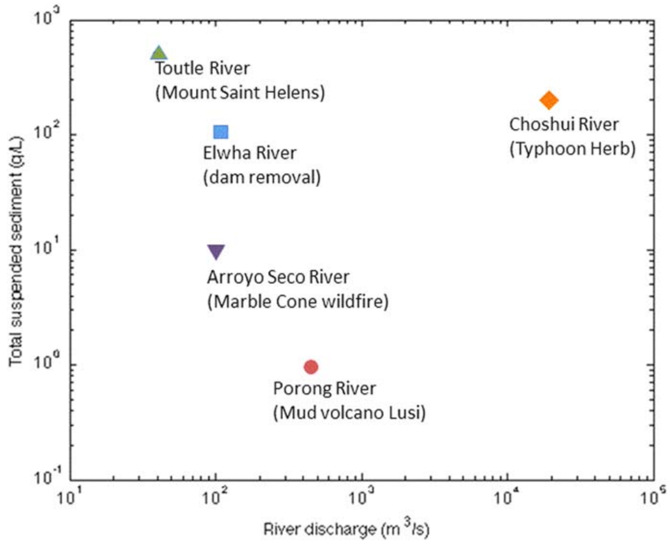

Fig. 8. Adapted from Jennerjahn et al. (2013). Examples of large-scale disturbances that resulted in significant amounts of sediment entering river systems around the world. Green triangle—North Fork Toutle River (Washington, U.S.A.) after the 1980 Mount St. Helens eruption (Major et al. 2007); orange diamond—Choshui River (Taiwan) after Typhoon Herb in 1996 (Milliman and Kao 2005); blue square—Elwha River (Washington, U.S.A.) after the full removal of the Elwha dam and partial removal of the Glines Canyon dam in 2013 (Magirl et al. in press); purple triangle—Arroyo Seco River (California, U.S.A.) after the Marble Cone Fire in 1977 (Warrick et al. 2012); red circle—Porong River (Java, Indonesia) in 2008 after the eruption of the mud volcano Lusi (Jennerjahn et al. 2013).

levels in the river (Magirl et al. in press) and in the estuary (Fig. 4a) increased significantly during these storms and subsequent high discharge events through the spring freshet. High turbidity levels in the estuary were also more prolonged in WY13 and WY14 than WY12. The increased duration of the high turbidity events in the estuaries was likely driven by a combination of increased suspended sediment in the river along with a reduction in tidal flushing.

Potential biological implications of change

The water quality and habitat changes we have seen in the Elwha River estuary complex are likely affecting the recruitment, growth, foraging, and survival of resident and migratory aquatic organisms that utilize the Elwha River estuary via multiple pathways. First, the loss of water flow through the estuary could lead to regime shifts in the water column and benthic sediment (Alpine and Cloern 1992; Austen et al. 2002) by changing nutrient dynamics, productivity, and flushing capacity (Nichols et al. 1986). Second, a change in the type and persistence of salinity habitats alters the species that are suited to those conditions (Edgar et al. 2000). Third, elevated turbidity decreases light availability for primary production (Davies-Colley and Smith 2001), and can reduce food availability (Brzezinski and Holton 1983) and the feeding rates and selectivity of juvenile salmon (Kern et al. 1986).

In addition to changes in water quality, deposition of up to a meter of fine sediment in the estuary (Warrick et al. in press) is also likely to affect biological communities (Henley et al. 2000; Thrush et al. 2003). Studies have shown that deposition of as little as 3 mm of sediment is enough to alter benthic invertebrate communities (Lohrer et al. 2004) and 9 cm of sediment can result in complete mortality and slow recovery (Norkko et al. 2002). Once estuarine benthic communities have been altered by sedimentation events, recovery time may be longer than in adjacent riverine communities (Reid et al. 2011). Changes in estuary productivity can reverberate through the food web and have lasting effects on the growth rates of salmon that experience suboptimal environmental conditions as juveniles (Morrongiello et al. 2014). Altered conditions in the Elwha estuary complex is already resulting in changes in the composition of primary producers and macroinvertebrate communities in the estuaries, along with shifts in fish community structure and juvenile salmonid diets (Beirne pers. comm.).

The removal of the Elwha and Glines Canyon dams and the subsequent delivery and deposition of sediment to the

Fig. 9. Different configurations of the channel that connects the east estuary to the river. Sediment accumulation in the channel tended to occur during high flows, subsequently disconnecting the estuary from the river and increasing the depth of the estuary. (Photos by M. Foley)

river delta has caused the Elwha River system to lose its small, but important estuary habitat. However, as the delta progrades seaward, the potential for new estuary habitat to develop is high (Fig. 2F). Although estuarine conditions have not yet manifested in the new pools forming on the east and west sides of the delta, we are monitoring physical and biological metrics in these newly formed areas to determine if viable habitat is starting to form seaward of the historical estuary complex.

The estuary conditions as of October 2014 are unlikely to represent the final configuration of the estuary because restoration actions for large-scale projects such as the Elwha can take years to evolve (Verdonschot et al. 2013). The physical and biological conditions are likely to continue to evolve over the next decade as the river moves the remaining reservoir sediment and ultimately settles into its natural sediment regime (Warrick et al. in press) and presumably a stable equilibrium (Suding et al. 2004). It is possible, however, that the early changes to the estuary we have documented have occurred so quickly and are so large that some of the changes will last decades (Stanley and Doyle 2003). We are continuing to monitor the physical and biological changes in the estuary to create a long-term record of the rate and magnitude of change, better understand how physical and biological changes are linked, and determine the role of the estuary—particularly for salmon—in its new configuration.

As sediment delivery and deposition increases due to anthropogenic and natural stressors in watersheds that promote the erosion of terrestrial sediment (Thrush et al. 2004), it is increasingly important to understand how sediment directly and indirectly affects the structure and functioning of ecosystems. Even though the removal of the Elwha and Glines Canyon dams is an extreme sedimentation event, research is necessary to help inform management decisions and restoration efforts, particularly for increasing discussions around dam decommissioning and the short and long-term tradeoffs associated with removals.

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